The European HiPER Programme: High Power Electric Propulsion Technology for Space Exploration

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High Power Electric Propulsion could play a key role in space exploration venture by enabling more affordable and sustainable space-to-space missions. Nevertheless, the ability to fully realize the benefits deriving from the application of advanced electric propulsion is also dependent upon the development of suitable electrical power sources. HiPER is a 3-year collaborative project substantially funded by the European Union and under the coordination of Alta aimed at laying the technical and programmatic foundations for the development of innovative Electric Propulsion technologies - and of the related power generation - to fulfill future space transportation and space exploration needs. The paper presents the proposed scenarios for High Power Electric Propulsion applications and the development status of the innovative technologies for future space exploration so far addressed in the programme.

I. Introduction

Electric Propulsion (EP) could play a very important role in future space exploration programmes by enabling more affordable and sustainable space-to-space missions. Today's state-of-the-art Electric Propulsion has achieved the capability to allow high efficiency "one shot" missions, such as those developed or under development for the European SMART-1, GOCE and Bepi Colombo spacecrafts, for the American Deep-Space 1 and DAWN, and for the Japanese Hayabusa[1-5]. What is needed next is the development of EP systems intended for the much larger payloads and re-use capability. Indeed, larger payload applicability can be achieved by increasing the operational power level of the propulsion systems.

HiPER - High Power Electric propulsion: a Roadmap for the future - is a 3-year collaborative project substantially funded by the European Union aimed at laying the technical and programmatic foundations for the development of innovative EP technologies - and of the related power generation - to fulfill future space transportation and space exploration needs. HiPER started on October 2008 and involves 20 partners from 6 European Countries under the coordination of Alta. The project's goal is very ambitious, since it not only addresses technologies, but also attempts to consider major technological efforts in the framework of social and political scenarios, both internal to Europe and with respect to non-European partners.

The first two years of activities have been mainly devoted to select mission scenarios which could benefit from the increase of the operational power level of Electric Propulsion systems and to initiate design and development activities of EP technologies and the related power generation. These development activities will be finished during the last year of the programme. High power Electric Propulsion application scenarios and the status of manufacturing, assembly and testing activities of the technologies developed in HiPER programme will be presented.

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II. HiPER Project Logic and Phases

The HiPER project is fully supporting the vision foreseen by the European Commission, which fosters a fruitful exchange of technologies between the commercial and scientific space transportation (or exploration) users. HiPER's objective will be pursued by conceiving and substantiating a long term vision for mission-driven Electric Propulsion development, considering realistic advances in state of the art of EP related technologies and performing basic research and proof-of-concept experiments on some of the key concepts identified by such a vision.

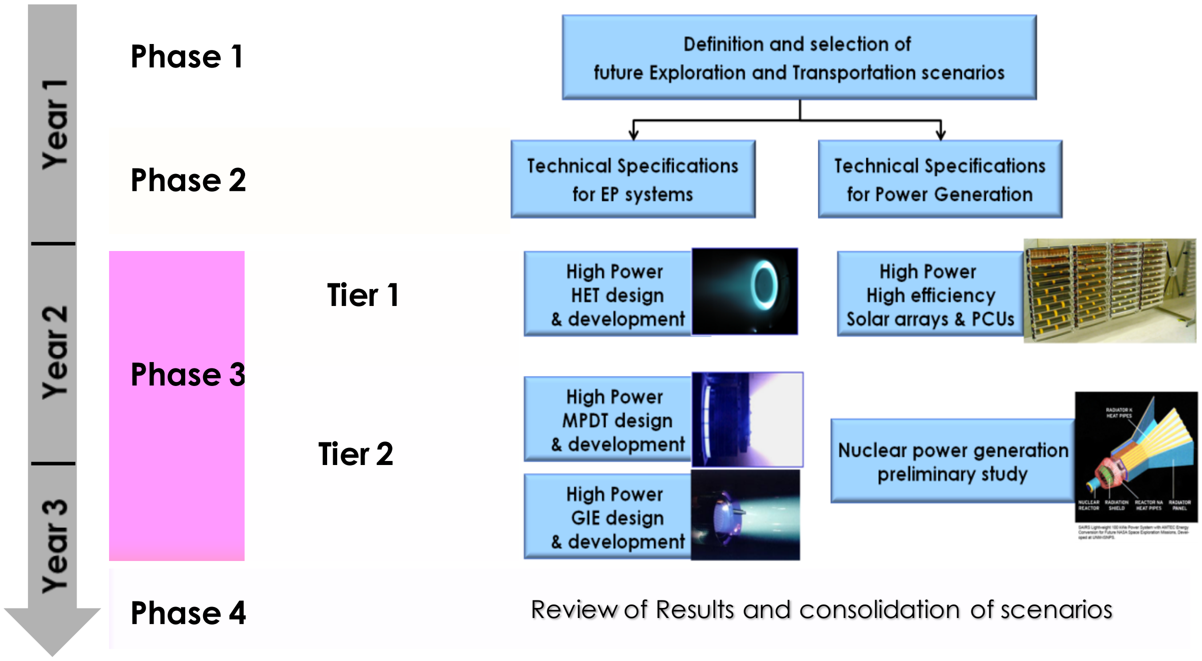

Figure 1. HiPER Project Logic and Phases

Project's tasks have been split into the following main phases (Fig. 1):

- *Phase 1*: Definition of future scenarios for European space transportation and exploration, and of ensuing possible mission objectives. The international framework and trends are also taken into account to build the reference scenario.
- *Phase 2*: Definition of requirements for power generation and Electric Propulsion, based on scenarios depicted in Phase 1.
- *Phase 3:* Design of power and propulsion subsystems, based on Phase 2 inputs. Some initial manufacturing and testing of components, subparts and/or subsystems will be also addressed, to the extent needed to fully justify and substantiate the overall strategic plan which will be the main output from Phase 4 below. The technology activities of this phase are performed by teams grouping the best available expertise in Europe for the various technologies. The Phase 3 activities will mainly be technological, and will be divided into Tier 1 and Tier 2 activities:
    - Tier 1 refers to technologies which are expected to play a major role in short to medium term scenarios (namely, Hall Effect Thrusters - HETs - and Solar Power Generation), and which will also have the most impact on present-day competitiveness of involved partners, being more directly of interest to the present space market; Tier 1 activities have been allocated a larger share of the budget because of their more urgent interest and larger short term impact.
    - Tier 2 refers to technologies which are expected to play an increasingly large role in long term scenarios (namely MagnetoPlasmaDynamic Thrusters – MPDT- advanced Gridded Ion Engines - GIEs - and Nuclear Power Generation) and which, although being farfetched at present, will be enabling cornerstone technologies for future, more ambitious space undertakings.
- *Phase 4:* Review of results of Phase 3 and consolidation of scenarios and missions from Phase 1. The main result from Phase 4 will be a fully substantiated technology and system development plan covering the needs of future

European space transportation and exploration, with experimental justification of the selected options (if needed) stemming from the technology building block activities.

III. Selected Scenarios for High Power Electric Propulsion Application

The definition of mission and transportation scenarios which could benefit from high power Electric Propulsion is an essential pre-requisite to complete a roadmap and long term technology planning study. EP flight heritage demonstrated a sustained capability for orbit maintenance, orbit raising, orbit change and topping, and a good agreement between flight and ground data. Nevertheless, new mission opportunities and additional benefits could derive from high power EP application. In particular, due to mass savings and launch flexibility, further missions could be enabled and performed in a more sustainable and affordable way. Furthermore, interplanetary transfers could be accomplished avoiding the need of gravity assist manoeuvres and - in some cases - even faster than missions using chemical propulsion.

The selected HiPER scenarios try to harmonize the medium-long term plans by the main space agencies and are compliant with a sustainable and affordable space exploration program based on visiting a series of locations and objects in the solar system with the objective to demonstrate critical and enabling technologies.

Therefore, also based on recent outcomes from US space exploration guidelines[6], some near and long term mission and transportation scenarios have been envisaged by the HiPER Mission Analysis team (Alta, Astos Solutions, CNES, Domaine de Beauregard, KopooS Consulting and Space Enterprise Partnerships) which could benefit from future high power EP technologies.

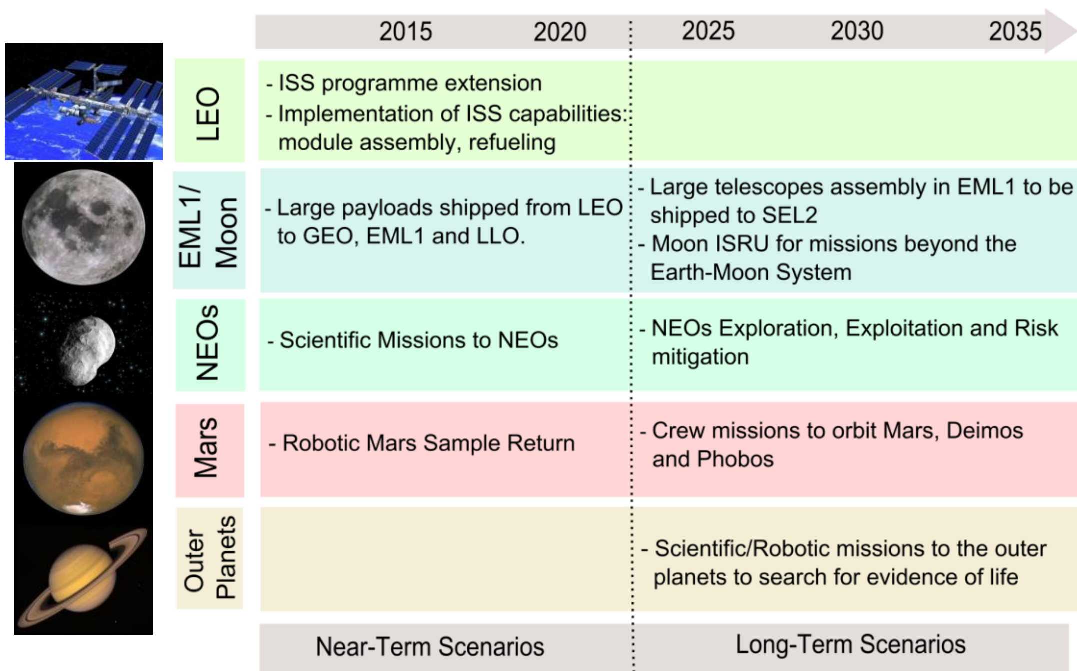

Figure 2. HiPER Selected Scenarios for High Power EP Application

The HiPER preliminary list of the most promising mission classes includes:

1) *Orbit transfer in the Earth-Moon system:* lessons learned from ISS in terms of routinary module assembly and refueling are directly applicable to the design, development, operations and management of future exploration missions. Large payloads could be shipped by means of high power EP from LEO to GEO, EML1 and LLO at expense of longer transfer times with respect to conventional propulsion systems. Once shipped, these large modules could be assembled in space to build a space hub or large telescopes in Lagrangian points with the possibility to be later shipped towards further destinations.
2) *Robotic Mars Sample Return (MSR):* considered as a key mission by all space agencies and a priority for Europe, MSR can represent an important milestone on an international roadmap leading to a human mission to Mars. It can also represent a very good candidate to exploit the benefit of EP (in combination with conventional propulsion) within a reasonable time-scale and with the need of a single launch. In addition to the high scientific value deriving by the analysis of the samples (composition, assessment of

evidence of prebiotic processes/past life, analysis of geological processes, etc..), it is recognized that MSR also would have a big impact on the public opinion, just the way it happened when Apollo samples returned from the Moon.

3) *NEOs exploration, exploitation and risk mitigation:* after some scientific/sample return missions to search for new resources, the exploitation of NEOs can potentially lead to commercial utilization of raw materials either on Earth and in-space. The capability to deflect threatening Earth-crossing asteroids can be also developed and thus contribute to increase mankind safety.
4) *Mars and its moons (Deimos and Phobos) fly-bys and science:* Mars and its moons fly-bys with crew and cargo missions to coordinate with or control robots on Mars surface.
5) *Outer Solar System and beyond robotic exploration:* scientific/robotic missions to outer planets of the solar system. In particular, missions to Jupiter's and Saturn's moons, Uranus and Neptune to search for evidence of life.

Some of them are grouped as *near term missions* that rely on the development of high power EP thrusters and on the use of Solar Electric Propulsion (SEP). SEP missions are designed employing solar panels to generate the required on-board power and their mission architectures are generally applicable to a wide range of missions. However, due to the rapid decrease of solar radiation flux that is an inverse relationship with the Sun distance squared, SEP missions are considered inappropriate for missions that go beyond Mars orbit[7]. Therefore, an alternative source of energy is mandatory for outer solar system exploration.

In a longer run, a nuclear power generation source coupled with high power EP thrusters will allow a wider range of mission classes as benefits deriving from NEP tend to grow with the distance travelled, especially away from the sun. Besides, a NEP system provides surplus power for on-board use. For instance, comfortable living conditions to the crew, redundant safety systems and active protection against solar and cosmic radiations can be assured.

IV. Solar and Nuclear Power Generation

A. Solar Power Generation

Currently, the multi panel deployable solar array is the most common system utilized for medium and high power applications. Its ability to provide accommodation for power growth (up to tens of kW), high reliability, competitive weight and low cost, lead to worldwide success and high maturation.

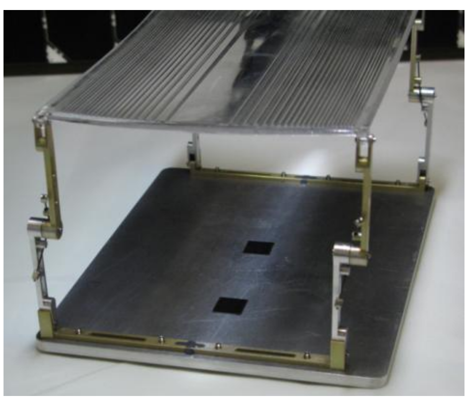

Figure 3. Optical System with shape memory alloy

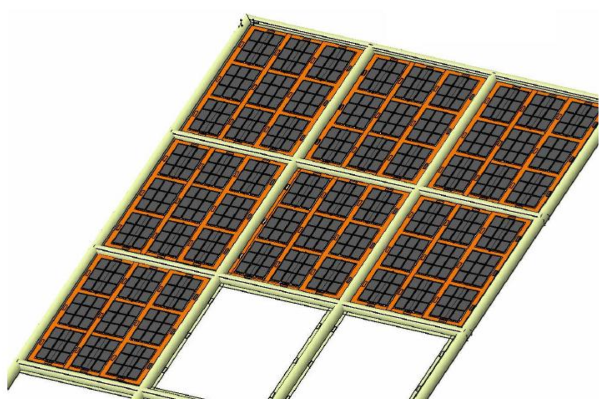

Figure 4. Design of the Inflatable Solar Generator

However, to increase the available power on board a spacecraft, a big step forward in terms of solar cell and substrate technology is needed to overcome mass and volume constraints imposed by state-of-the-art technology. Light concentration techniques, thin solar cells and light/flexible substrates are going towards this direction.

Starting from that, Selex Galileo, Fraunhofer ISE, Politecnico di Milano and Aero Sekur initiated several research and development activities in the areas of solar cells technology, light and flexible substrate (packed and deployed throughout memory alloy structures integrated to the substrate), super-elastic (or shape memory alloy) frame for the solar concentrator structure and optical Fresnel lenses for solar concentration (Fig. 3) and solutions for Photo Voltaic Assembly (PVA) integration on flexible substrate (Fig. 4). Objective of the solar power generation team is to design and develop a solar power generator able to produce up to 250 kW with a specific power of about

100 W/kg and a stowed power density of about 20-30 kW/m^3. For functional verification, in HiPER programme only a breadboard model of dimension 6540 x 1860 mm^2 was built, composed of three single elements (Fig. 5).The frame is composed of Aertex inflatable beams to tension the membranes which sustain the solar cells, the substrate is made of Kapton, Vectran and nylon textile frame. Moreover, the investigation of the Power Management And Distribution (PMAD) system capable to fulfil the requirements of both solar and nuclear energy sources has been carried out. The main bus voltage is regulated at 300 V with the possibility of direct drive with thrusters and a current level of about 800 A. Strings of Li-ion batteries will dump energy oscillations during fast power fluctuations induced by thrusters.

Figure 5. Solar Generator Breadboard Model composed of only 3 elements

B. Nuclear Power Generation

Previous studies have shown that nuclear power generation specific mass decreases as system power increases. However the mass penalties associated with other aspects of increasing power, such as power conditioning and distribution, may offset some of the benefit. Moreover, further constraints are imposed by assumptions about launch lift capability and fairing dimensions. During the HiPER study, the Nuclear Electric Power (NEP) generation technical roadmap was produced in which the achievable performance and design characteristics of a nuclear fission reactor for power generation consistent with the candidate mission requirements were identified.

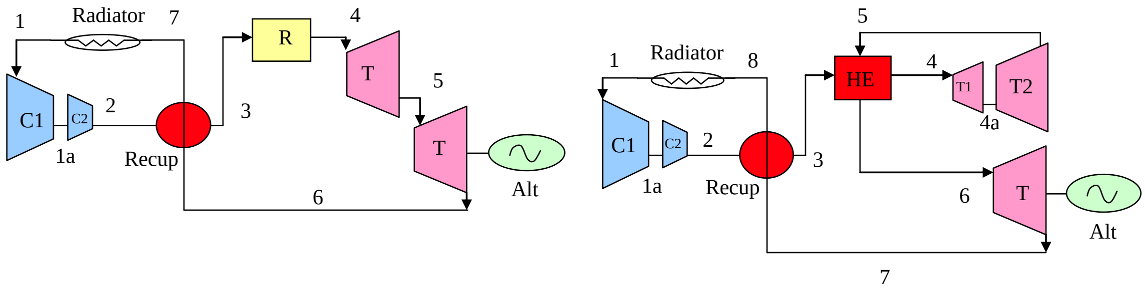

Figure 6. Direct (on the left) and indirect NEP Brayton cycle

Starting from the design constraints - launch mass and volume fixed by Ariane 5 ECA performance - and system design considerations, the nuclear power generation team (Space Enterprise Partnerships, Rolls Royce and Acta) has identified the NEP concept design targets:

1) Lifetime: 10 years operations and 15 years overall
2) Power level: 200 kWe (1 – 1.2 MWth)
3) Direct Gas or Indirect Liquid Metal Cooled Reactor (Fig. 6)
4) Brayton cycle power conversion
5) Specific mass range of 30–38 kg/kW:
   - NEP Generator: 28-34 kg/kW

- Power Management And Distribution (PMAD) system: 2-4 kg/kW

6) Low volume high density fixed or high volume low density deployable radiators

In Table 1, results from concept design options are shown

Table 1. NEP System Concept Design Options

System & Baseline Example	Direct Fixed Radiator	Indirect Deployable Radiator	Direct Fixed Radiator
T hot, K	1500	1200	1300
Power MWth MWe	 1.183 0.2	 1.117 0.2	 1.183 0.2
η	0.169	0.179	0.169
Reactor Mass (kg)	1627	528	1627
Shield (kg)	800	975	800
Reactor Control (kg)	42.6	31.1	42.6
IHX (kg)		366	
Generation (kg)	1656	1612	1656
Radiator Area (m^2) Mass (kg)	 80.8 1441	 225 1798	 143 2589
Total Mass (kg)	5566.6	5310	6714
Specific Mass (kg/kWe)	27.83	2655	33.57

The identification of the technical developments, management requirements and risk management measures necessary to realize these targets were also investigated. In addition, a preliminary definition of the PMAD architecture was also investigated to define boundary requirements applicable to both solar and nuclear power generation systems.

V. HiPER Electric Propulsion Technologies

Three different EP concepts were investigated in HiPER programme as at present these technologies are considered as the candidates with the highest application potential: Hall Effect Thrusters (HET), Gridded Ion Engines (GIE) and MagnetoPlasmaDynamic Thrusters (MPDT). Each of the three has characteristics which make it particularly suitable to a specific class of mission.

A. Hall Effect Thruster

Based on state-of-the-art HET technology and on up-scaling process[8-11], the HET Team (Snecma, Alta, CNRS, IPPLM, Onera and Tecnalia) started the design of the 20 kW prototype (Fig. 7) able to provide 1 N thrust at an Isp of 2500s (Table 2).

Activities on HET were focused on the assessment of the material options for the anode, to initiate activities aimed at improving of the ceramic process for increased diameter ingots and at measuring ceramic erosion and secondary electron emission in order to choose the best anode ceramic. Plasma modeling was also carried out to simulate the thermal loads and the magnetic field topology was also investigated to achieve the best focusing of the plume. After the design phase, the HiPER "PPS-20k ML" HET prototype was manufactured. Manufacturing of discharge channel was performed by Tecnalia; two cylindrical blocks hot pressed with an external diameter of 375 mm and height of 118 mm were already manufactured and machining process was completed to obtain the desired geometry. Assembly phase of the high power HET prototype has been recently performed and testing activities are on the way in Onera Pivoine facility at a reduced power level of 10 kW. Results of test campaign will be available at the end of this summer.

B. Gridded Ion Engine

The high power Gridded Ion Engine (GIE) Team (Alta and University of Southampton) focused on establishing future GIE requirements, to assess how they might best be met, to estimate performance levels that might be achieved within the limits of current knowledge, to expand technical information in one specific critical area, and

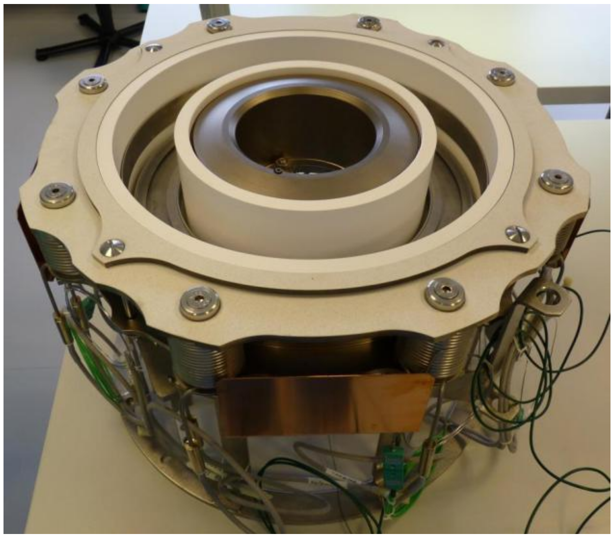

Figure 7. HET prototype"PPS-20k ML"

Table 2. "PPS-20k ML" main specification

Power (kW)	20
Thrust (N)	1
Specific Impulse (S)	2500
Discharge Current (A)	40
Discharge Voltage (V)	500
Xenon mass flow rate (mg/s)	~41
External Diameter (mm)	320
Height (mm)	~110
Mass (kg)	~25

prepare a roadmap to indicate how progress might be made in the future, given appropriate funding. To address the need for higher thrust density a novel GIE concept was envisioned by Dave Fern[12], where the ion extraction – and therefore the current density – and the ion acceleration processes are decoupled. Based on this concept and on mission requirements deriving from the mission analysis, the definition of the most important geometrical and functional parameters and the optimized preliminary design of the Dual-Stage 3 Grids (DS3G) ion thruster and of its high current hollow cathode were carried out. Testing activities of 188 A Hollow Cathode (HC) (Fig. 8)are in progress and results will be available at the end of this summer. Main objective of the test is to demonstrate the capability of the cathode to survive a 500 hour test.

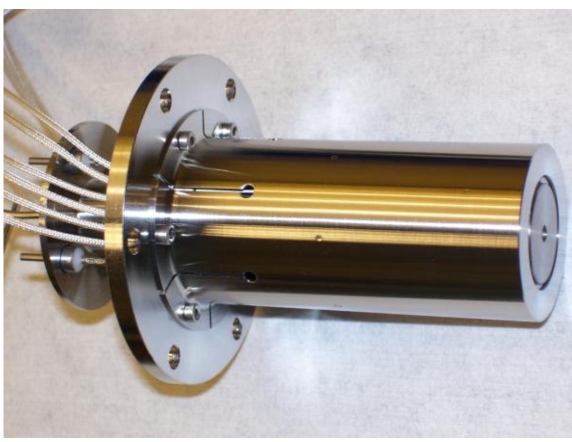

Figure 8: DS3G 188 A Hollow Cathode (HC)

Table 3. HiPER DS3G Ion Thruster main specifications

Power	25 kW
Isp	10000 s
Thrust	0.45 N
Screen grid voltage	8120 V
Extraction grid voltage	6120 V
Accelerating grid voltage	-120 V
HC Discharge current	187.9 A
HC Mass flow	4.8 mg/s
Cathode radius	5 mm

C. Magneto Plasma Dynamic Thruster

Activities of the MagnetoPlasmaDynamic Thruster (MPDT) team (Alta, Consorzio RFX and IRS-University of Stuttgart) during the first two years of HiPER programme were focused on the definition of the most important MPD thrusters geometrical and functional parameters, the characterisation of plasma instabilities in MPD thrusters, the identification of design solutions for instability control and the validation of the main design choices for high-efficiency AF MPD thrusters. The design, manufacturing and assembly of two development models in Alta and in Stuttgart (Fig.9 and Fig. 10) were completed. Then, testing activities will be carried out and will aim at investigating

Figure 9. 100 kW unsteady MPDT on balance @ Alta

Table 4. 100 kW Alta MPDT main specifications

Power (kW)	100
Thrust (N)	2.5
Specific Impulse (s)	2500
Nominal Current (A)	2100
Mass flow (mg/s)	80
Anode Diameter (mm)	135
Anode-to-cathode radius ratio	3
Mass (kg)	18.5

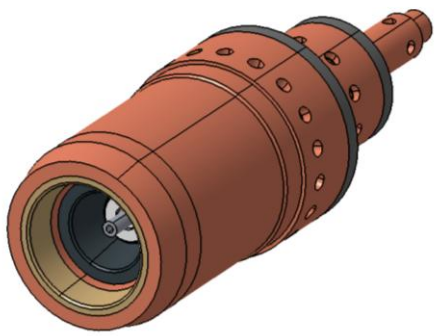

Figure 10. IRS-USTUTT 100 kW Stationary MPDT

Table 5. 100 kW IRS-USTUTT MPDT main specifications

Power (kW)	100
Thrust (N)	>2.5
Specific Impulse (s)	~3000
Nominal Current (A)	1000
Discharge Voltage (V)	500
Mass flow (mg/s)	100
Anode Diameter (mm)	85
Anode-to-cathode radius ratio	8.5

Figure 11. Alta multichannel 180 A cathode (on the left) and during the test campaign @ Alta

plasma instability issues and at addressing possible solutions for efficiency improvement. Test campaign in Alta is in progress and propellant used are Xenon and Argon.

As regards development activities of high current cathodes, several multi-channel hollow cathodes were investigated (Fig. 11) to assess erosion rates. Indeed, MPD cathodes are very critical parts of the thruster. Testing activities for 140 hours of operation and 100 cycles were performed in Alta on the multichannel cathode and a huge amount of data was recorded such as electrical characteristics at different flow rates and temperature profiles at different flow rates and currents. Test results will be also used to improve the model for successive design of full-scale cathode for thruster engineering models.

VI. Conclusion

During the first two years of activities, the HiPER programme has been focusing on the selection of mission scenarios which could benefit from high power Electric Propulsion and on the design and development of future EP technologies and of related power generation systems. Indeed, the combined use of EP thrusters with high power generation systems can enable a wide range of mission classes compatible with flexible architectures for space exploration.

As regards in-space high power generation systems, the nuclear power generation technical roadmap was produced in which the achievable performance and design characteristics of a nuclear fission reactor for power generation consistent with the candidate mission requirements were identified. In addition, the design of high power inflatable solar concentrator was carried out. A breadboard model has been manufactured and will be tested for functional verification. Besides, the definition of the Solar Electric Power Subsystem architecture has been also outlined in order to define boundary requirements applicable to both solar and nuclear power generation systems.

As regards high power electric thrusters, first two years of HiPER activities were mainly aimed at reporting the technological assessment of all electric thrusters concepts studied - Hall Effect thrusters, Gridded Ion Engines and MagnetoPlasmaDynamic thrusters - and at defining preliminary design specifications. After completion of design activities, during the last year prototypes of the 20 kW HET, 100 kW MPDT - for both steady and unsteady operation modes - and the 188 A hollow cathode for high power Ion thruster were manufactured. Besides, most of assembly activities are already completed whilst testing activities of prototypes are under way and results of test campaigns will be available at the end of summer.

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